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Single-Phase Rectifier With Near Sinusoidal Input Current

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Abstract-The paper proposes a new uncontrolled single-phase rectifier, which does not inject inadmissible current harmonics in the AC mains. Such a rectifier does not necessitate on the AC side classic passive filters or active filters and on the DC side boost choppers. The functioning stages of the proposed converter as well as its characteristics are established and, on this basis, design considerations are commented. Finally, possible application of these converters are presented.

Keywords: AC- DC power conversion, power quality, power system harmonics, static frequency converters, uncontrolled single phase rectifiers.

I. INTRODUCTION

In most power electronics applications, the power supply input is in the form of 50 or 60 Hz, sine wave AC voltage provided by the electric utility, that is first converted to a DC voltage. Increasingly, the trend is to use inexpensive single-phase rectifier to convert input AC into DC in an uncontrolled way. A large majority of the power electronics applications, such as switching DC power supplies, AC motor drives for traction, DC servo drives, and so on, use such uncontrolled single phase rectifiers [1,2]. The single-phase diode bridge rectifier is a commonly used circuit configuration. An important drawback of this rectifier is the injection in the power supply of higher order harmonics of input current of inadmissible values.

A first alternative to reduce the current harmonics is the usage of passive filters made of inductors and capacitors, as shown in fig. 1a. In this figure, C_{dl} placed directly across the rectifier bridge is small as compared to C_d. This allows a larger ripple in V_{dl}, but results in an improved waveform of i_s (Fig. 1b). The ripple in V_{dl} is filtered out by the low-pass filter consisting of L_d and C_d. The important disadvantages of such an arrangement are cost, size, losses and the significant dependence of the average DC voltage V_d on the power drawn by the load [2].

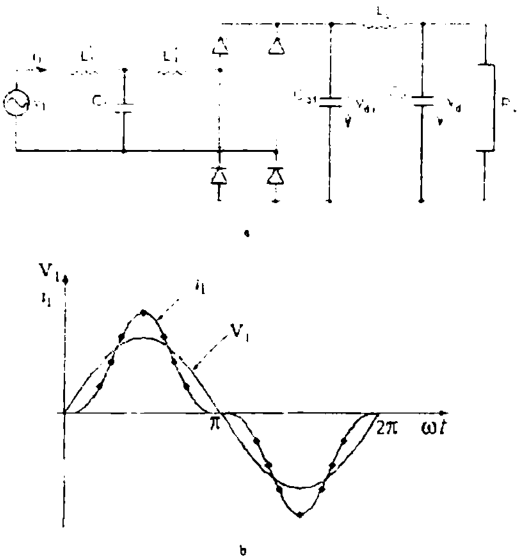

Fig. 1. Passive filters to improve the phase current waveform
(a) Passive filter arrangement
(b) Current waveform.

Active power filters consisting of voltage- or current- source PWM inverters have been studied and put into practical use because they have the ability to overcome the drawbacks inherent for passive filters [3], [4]. The active filter eliminates the harmonics that are present in the AC lines by injecting the compensating current into the AC side. However, the active filters have the following disadvantages:

Difficulty to construct large-rated current sources with a rapid current response;

High initial and running costs.

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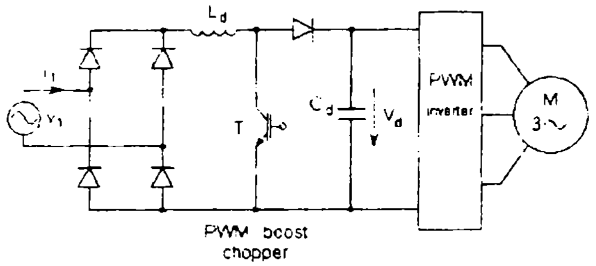


Fig. 2. Single-phase diode rectifier with boost chopper for active line current shaping.

Another alternative to reduce the current harmonics is the usage of AC/DC converters consisting in single – phase diode rectifiers cascaded with a PWM boost chopper as shown in Fig. 2 [1], [5]. The boost chopper basically provides two functions: (i) it regulates the capacitor voltage wich should always be higher than the peak line voltage, and (ii) it controls the inductor current so that the line current is sinusoidal at unity power factor. However, the single-phase diode rectifier with boost chopper have the main disadvantage of high initial and running costs.

In what follows we present a new uncontrolled single-phase rectifier, which does not inject inadmissible current harmonics in the AC mains. Such a rectifier does not necessitate on the AC side classic passive filters or active filters and on the DC side boost choppers. This converters is named for short in what follows RLCD (Rectifier with Inductor, Capacitors and Diodes).

II. NEW CONVERTER CONFIGURATION

In Fig. 3a we present a new AC/DC single-phase converter generating reduced higher order current harmonics in the mains [6]. The capacitors C_1 – C_4 have the same value C and they are DC capacitors [6]- [8]. The inductor L is connected on the AC side. The values of L and C fulfill the relation :

$$0.20 \le LC\omega^2 \le 0.30 \qquad (1)$$

in order for the phase current i_1 to be practically sinusoidal, according to Fig. 4b. ω denotes the mains angular frequency. The working principle of this rectifier can be explained by the help of the following four stages which last for one mains period $T = 2\pi/\omega$.

Stage 1

The current $i_1^{(1)}$ varies from zero to I_1 (Fig. 4b), the current i_d is zero, the voltage v_{C1} decreases from V_d to zero and v_{C3} increases from zero to V_d. This stage lasts between 0 and t_1 and the corresponding equation is:

$$V_1 \sin(\omega t + \varphi) = L\frac{di_1^{(1)}}{dt} + \frac{1}{C}\int_0^t i_1^{(1)}\,dt - V_d \qquad (2)$$

The solution of this equation is:

$$i_1^{(1)} = V_1 \frac{C\omega}{1-LC\omega^2}\left\{\cos(\omega t + \varphi) + \frac{\omega_0}{\omega}\left[\frac{2V_d}{V_1}\left(1 - LC\omega^2\right) - \sin(\omega t_1 + \varphi) + \sin\varphi\right]\frac{\sin\omega_0 t}{1 - \cos\omega_0 t_1} + \frac{\cos\omega_0(t - t_1) - \cos\omega_0 t}{1 - \cos\omega_0 t_1}\cdot\cos\varphi\right\} \qquad (3)$$

in which the angular frequency ω_0 fulfills the condition:

$$LC\omega_0^2 = 1 \qquad (4)$$

Stage 2

The current $i_1^{(2)}$ varies from I_1 to zero (Fig. 4b), the current $i_d = i_1^{(2)}$ and the diodes D_1 and D_2 are conducting. This stage lasts from t_1 to $\frac{\pi}{\omega}$ and the equation describing the circuit evolution is:

$$V_1 \sin(\omega t + \varphi) = L\frac{di_1^{(2)}}{dt} + V_d \qquad (5)$$

The solution of this equation is:

$$i_1^{(2)} = \frac{V_1}{L\omega}\left\{-\cos(\omega t + \varphi) - \frac{V_d}{V_1}(\omega t - \omega t_1) + \frac{\cos(\omega t_1 + \varphi) + LC\omega^2\cos\varphi}{1 - LC\omega^2} + \frac{\omega}{\omega_0}\left[\frac{2V_d}{V_1} - \frac{\sin(\omega t_1 + \varphi) - \sin\varphi}{1 - LC\omega^2}\right]\frac{\sin\omega_0 t_1}{1 - \cos\omega t_1}\right\} \qquad (6)$$

Stage 3

The current $i_1^{(3)}$ varies from zero to $(-I_1)$ according to Fig. 4b, the current i_d is zero, the voltage v_{C1} increases form zero to V_d, and the voltage v_{C3} decreases from V_d to zero. The stage lasts from $\frac{\pi}{\omega}$ to $\frac{\pi}{\omega}+t_1$ and its associated equation has the following form:

$$V_l\sin(\omega t+\varphi)=L\frac{di_l^{(3)}}{dt}+\frac{1}{C}\int_{\frac{\pi}{\omega}}^{\frac{\pi}{\omega}+t} i_l^{(3)}\,dt+V_d \qquad (7)$$

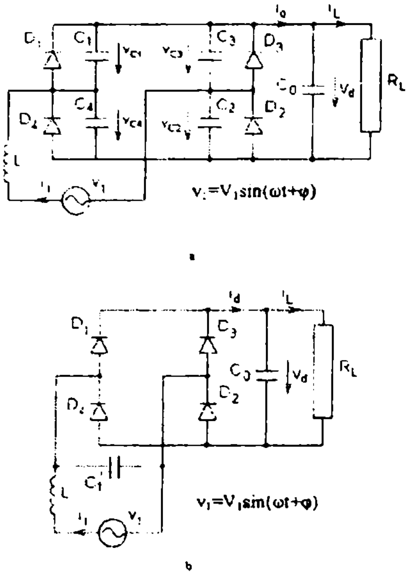


Fig. 3. Single-phase rectifier with almost sinusoidal input current

(a) With four DC capacitors

(b) With one AC capacitor

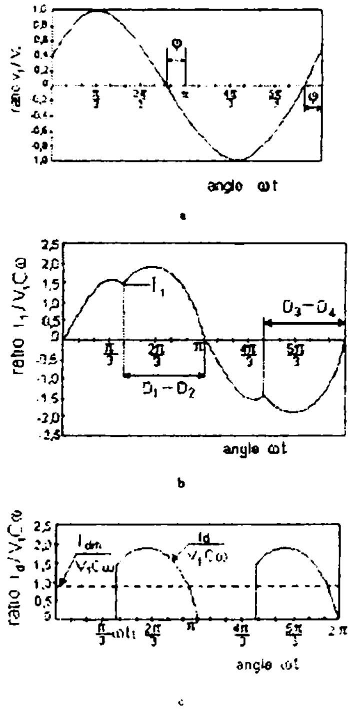


Fig. 4. Waveforms for RLCD converter

(a) Voltage v_l

(b) AC line current i_l.

(c) DC current i_d

Stage 4

The current $i_l^{(4)}$ varies from ($-I_l$) to zero according to Fig. 4b, the current $I_d = -i_l^{(4)}$ and the diodes D_3 and D_4 are conducting. This stage lasts between $\frac{\pi}{\omega}+t_1$ and $\frac{2\pi}{\omega}$, and the associated equation is :

$$V_l\sin(\omega t+\varphi)=L\frac{di_l^{(4)}}{dt}-V_d \qquad (8)$$

In Fig. 4b we present the variation of the ratio $i_l/V_lC\omega$ and in Fig. 4c the variation of the ratio $i_d/V_lC\omega$ versus the angle ωt, for the case $LC\omega^2=0.3$, $V_d=\frac{2}{\pi}V_l$ and $\varphi=25°$.

A constructive alternative for the RLCD converter is presented in Fig. 3b. For the same load R_L as in the circuit from Fig. 3a, in the new scheme, the capacitor C'_1 is mounted on the AC side and has the capacitance 2C. During the functioning, the capacitor C'_1 charges at a maximum voltage equal to ± V_d. The input current i_l remains the same.

III. RLCD CONVERTER CHARACTERISTICS

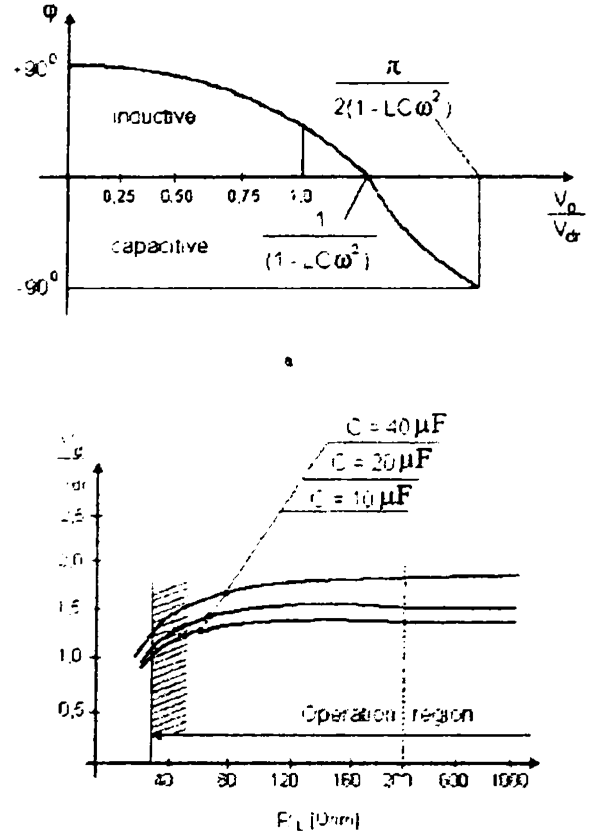
In order to design the single-phase rectifier presented in Fig. 3a, one can use relation (9), which is obtained from the condition that the values of the current i_l when transiting from one stage to the other to be identical :

$$V_d\left[\frac{\omega}{\omega_0}(\pi-\omega t_1)-\frac{2\sin\omega_0 t_1}{1-\cos\omega_0 t_1}\right]=$$
$$=\frac{V_l}{1-LC\omega^2}\left\{\frac{\omega}{\omega_0}\left[\cos(\omega t_1+\varphi)+\cos\varphi\right]-\sin(\omega t_1+\varphi)+\sin\varphi\right\} \qquad (9)$$

as well as relation (10), in which I_{dm} represents the mean value of the current i_d according to Fig. 4c :

$$I_{dm}=\frac{V_l}{\pi L\omega}\left\{\sin(\omega t_1+\varphi)+\sin\varphi-(\pi-\omega t_1)\cos\varphi+\frac{V_d}{V_l}(\pi-\omega t_1)^2\right\} \qquad (10)$$

There are two extreme cases during converter operation. In the fist case, if R_L= 0 (and so V_d = 0), the capacitors $C_1 - C_4$ are short - circuited and the angle φ = 90° is inductive. In the second case, if the voltage exceeds the value $V_1/(1-LC\omega^2)$, the diodes D_1 - D_4 do not conduct any more and the angle $\varphi = -90^\circ$ is capacitive.



a

b

Fig. 5. Variations of the parameters for the RLCD converter
(a) Angle φ
(b) Ratio V_d/V_{dr}

Fig. 5a depicts the variation of the angle φ, the phase displacement angle between the input voltage V_1 and the fundamental of the input current, as a function of the mean rectified voltage V_d rated to the reference value $V_{dr} = 2V_1/\pi$ characteristic for the classic single-phase rectifier. The voltage V_d can be established at a certain value by the load current i_L.

In order to choose the capacitors C_1-C_4, besides the necessity to determine the maximum mean rectified voltage $V_1/(1-LC\omega^2)$, one has to determine the rms current I_{CRMS} that flows through such a capacitor (Fig. 4b and 4c)

$$I_{CRMS} = \sqrt{\frac{1}{2\pi}\int_0^{\omega t_1} 2\left(\frac{i_1^{(1)}}{2}\right)^2 d\omega t} \qquad (11)$$

and supposing that the waveform of the input current is practically sinusoidal :

$$i_1 \cong I_{max}\sin\omega t \qquad (12)$$

it implies :

$$I_{CRMS} = \frac{I_{max}}{2}\sqrt{\frac{1}{2\pi}\left[\omega t_1 - \frac{\sin 2\omega t_1}{2}\right]} \qquad (13)$$

In order to ensure a smaller higher order harmonic content injected in the AC mains, the angle ωt_1 is recommended to vary between the limits:

$$25^\circ \le \omega t_1 \le 70^\circ \qquad (14)$$

and, in this case, I_{CRMS} is limited by

$$0.0461 \cdot I_{max} \le I_{CRMS} \le 0.1893 \cdot I_{max} \qquad (15)$$

Due to the fact that the currents that flow through the capacitors C_1 – C_4 have small values as compared with I_{max}, in order to get the necessary ωt_1 angle, it implies that one has to choose (for continuous operation) capacitors with relatively large rated capacitance C_R and rated voltage V_R. The condition is better fulfilled by the DC capacitors, as, for example, those in the series B 25355 for Smoothing, Supporting, Discharge [8]. At an approximately same volume, DC capacitors have a larger C_RV_R as compared with the AC capacitors; in exchange, they have smaller rated current I_R. For applications using RLCD there is no need for capacitors with large I_R.

Fig. 5b presents the variation of the output voltage V_d normalized with the reference value V_{dr} as function of R_L and C. For the inductor L, in accordance with Fig. 3a and b, we have adopted the value of 75 mH. Using these diagrams one can draw the following conclusions:

Once the value of C is increased, the value of the output voltage increases too.

The input current i_1 is practically sinusoidal for large variations of the load resistor R_L.

IV. POSSIBLE APPLICATIONS OF THE RLCD CONVERTERS

A possible application of the RLCD converters is their usage in static frequency converters with DC voltage link, designed for supplying with variable voltage and frequency the three-phase induction motor drives. In this case, the asynchronous drives are connected to the outputs of the PWM three-phase inverters, in accordance with Fig. 6a.

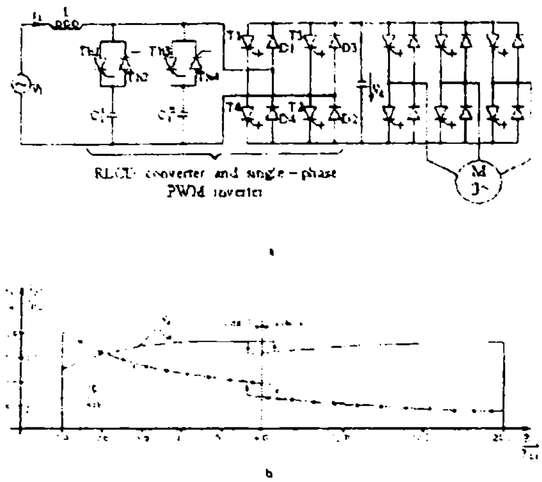


Fig. 6. Static frequency converter with DC voltage link
(a) Circuit configuration
(b) RLCD converter operation characteristics

It is also possible to design a static frequency converter with DC voltage link using the AC-DC converter operating in four quadrants . This AC-DC converter is made up of a RLCD converter with diodes D_1 – D_4, capacitors C_1', C_1'' and the inductor L. In order for the converter to operate in four quadrants the GTOs T_1 – T_4 and the thyristors Th_1 – Th_4 have been used. When the load consumes electric energy in zones 1 and 2 (for example when the asynchronous machine operates in motoring mode) the capacitors C_1' and C_1'' are connected through the command of the thyristors Th_1 – Th_4, while the GTOs T_1 – T_4 remain off. The energy is transmitted from the source to the capacitor C_0 by means of the circuit L, C_1', C_1'' and the diodes D_1 - D_4 .

In the first zone of operation, according to Fig. 6b, the RLCD converter operates with both capacitors C_1' and C_1'' connected at the input (the ratio C_1''/C_1' has the optimum value equal to 2). In this situation, one can obtain greater values for the voltage V_d and the amplitude of the mains current $I_{(1)}$, if the ratio R_L/R_{Lr} varies for example between 1 and 6 (where by R_{Lr} we have denoted the rated load resistance, for which the angle $\varphi = 0^{\circ}$) . In order to decrease the value of the capacitive current sent back in the mains at lower load powers (that is for larger values of the ratio R_L/R_{Lr}, between 6 and 24), in the second zone of operation, the thyristors Th_1 and Th_2 are blocked and so the capacitor C_1' is disconnected from the input of the RLCD converter.

Next, in order to further decrease the value of $I_{(1)}$, in the third zone, one blocks , the thyristors Th_1 – Th_4 , and so, both capacitors C_1' and C_1'' are disconnected. In this case, the GTO thyristors T_1 – T_4 are controlled following the PWM principle and the AC-DC converter in the input operates in the forced-commutated rectifier region, being constituted of the inductor L, the GTO thyristors T_1-T_4 and the diodes D_1 D_4. In this way one can transmit a reduced energy to the DC voltage link, and the angle φ can be maintained practically zero. In order to avoid possible oscillations at the transition from one zone to another, one can provide a hysteresis. Using this three operation zones method one can obtain a ratio between the maximum and the minimum value of the amplitude of $I_{(1)}$ varying between 10 and 20.

When the asynchronous drive is operating in regenerative mode and the voltage V_d is greater than $\pi V_{dr}/2(1-LC\omega^2)$, the single-phase PWM inverter operates in order to retransmit the energy received by the capacitor C_0. The PWM inverter is made up of the GTOs T_1 - T_4, the inductor L and the diodes D_1 – D_4 .One can conclude that the total operation duration of the single-phase inverter is much smaller than that of the RLCD converter. Obviously, in the regenerative operation mode, the capacitors C_1' and C_1'' remain disconnected.

Comparing the static frequency converter according to Fig. 6a with the single-phase PWM converter operating in four quadrants (with one inductor on the AC side, 4 switches and 4 diodes), it implies that the first alternative has a greater reliability. This is explained by the fact that in zone 1 and zone 2, with large duration, the operation of the thyristor T_1 – T_4 is not necessary. Also, the first AC-DC converter variant has the advantage of smaller losses.

Of course, the most numerous applications of the RLCD converter, according to fig. 3a or 3b, can be the DC voltage supply for practically constant loads.

IV. EXPERIMENTAL AND SIMULATION RESULTS

Laboratory experiments and simulation results have proved the effectiveness of the proposed single-phase low-harmonic rectifier. The laboratory prototype according to Fig. 3(a) consists of a single-phase voltage supply (with $V_{\tilde{m}}$ = 250V anf f=50Hz) and the RLCD converter. This converter is composed of four diodes, an inductor L and four DC capacitors with capacitance 20μF or 80μF. For the inductor L we have adopted the value 75mH. The filtering capacitor C_0 is 1000μF and the load resistor R_L can be varied between 40 Ω and 200 Ω.

In tables 1,2 and 3 we present the values of the rectified voltage, V_d , the amplitude of the line current, I_l, the amplitude of the third harmonic of the line current $I_{l(3)}$ and the total harmonic distorsion factor for the line current, THD for three distinct cases: (1) the capacitors C_1-C_4 have the capacitance 20μF, (2) the capacitors C_1-C_4 have the capacitance 40μF and (3) the capacitors C_1-C_4 have the capacitance 80μF . Using these tables one can draw the following conclusions:

Once the value of the capacitance C is increased, the value of the output voltage is increased too;

The input current i_l is practically sinusoidal for large variations of the load resistor R_L.

V_d[V]	I_l [A]	$I_{l(3)}$[A]	THD[%]
200	8.79	1.05	12.61
240	5.86	1.19	21
247	4.47	1.16	26.68
249	3.75	1.12	30.5
249	3.32	1.08	33

Table 1. Converter parameters for C_1-C_4 20μF

V_d[V]	I_l [A]	$I_{l(3)}$[A]	THD[%]
233	11.81	1.07	9.38
307	9.7	1.23	12.91
320	8.19	1.14	14.16
323	7.29	1.04	14.45
323	6.72	0.95	14.3

Table 2. Converter parameters for C_1-C_4 40μF

V_d[V]	I_l [A]	$I_{l(3)}$[A]	THD[%]
260	16.9	0.96	5.7
450	20.6	1.28	6.3
540	21.13	1.24	6
575	20.58	1.13	5.47
588	19.8	0.97	5

Table 3. Converter parameters for C_1-C_4 80μF

IV. CONCLUSIONS

A new uncontrolled single-phase rectifier, which does not inject inadmissible current harmonics in the AC mains was proposed. Investigating the working principle and converter characteristics, a possible application in static frequency converters with DC voltage link, designed for supplying with variable voltage and frequency the three-phase induction motor drives was suggested.

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